SPATIAL CONTROL OF CRYSTAL TEXTURE BY LASER DMD PROCESS

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Abstract

Turbine blades with controlled textures such as directionally solidified and single crystal structures have proven to have much improved ductility and longer thermal and fatigue life. It has been further reported that the benefits of single-crystal over conventionally cast as well as directionally solidified components critically depend on avoiding the introduction of defects, such as stray grains, freckles, or deviations from the required crystal orientation. Laser-based direct metal deposition (DMD) process equipped with proper sensors and NC devices helps in overcoming those hurdles to fabricate the blades with controlled texture. It appears that thermal control to provide uniform heat flow as well as spatial control of crystal texture by process feedback control is essential. The paper discusses about how to establish process conditions and thermal control requirements, development of a laboratory scale DMD process for spatial control of crystal texture, and mechanical properties of texture-controlled Ni-based superalloy turbine blade components.

Keywords: DMD Process, Texture Control, Closed-loop Feedback Control, Thermal Control

Introduction

Directionally Solidified (DS) or Single-crystal (SX) turbine airfoils have proven to have as much as nine times more relative life in terms of creep strength and thermal fatigue resistance and over three times more relative life for corrosion resistance, when compared to equiaxed crystal counter parts [1]. Modern high turbine inlet temperature jet engines with long life would not be possible without the use of DS or SX turbine airfoils. Especially by eliminating grain boundaries, it has been reported SX airfoils have much longer thermal creep and fatigue life and are corrosion resistant. They can be cast with thinner walls, meaning less material and less weight, but endure at a higher melting point temperature. These improvements all contribute to higher efficiencies.

Turbine blades in DS or SX form are routinely cast from nickel-based super alloys, since they offer improved performance and durability. However, the benefits of SX as well as DS over conventionally cast components critically depend on avoiding the introduction of casting defects, such as stray grains, freckles, or deviations from the required crystal orientation. Avoiding these defects is difficult in blades where the service load is at an angle relative to the axis of the blade and hence the <001> crystallographic orientation of the blade should be cast in alignment to the load.

Direct Metal Deposition (DMD) provides an economical and flexible layered manufacturing solution for this advanced Gas Turbine Technology. In comparison with conventional laser cladding processes, DMD controls the heat input in to the substrate (blade) with an intelligent closed-loop feedback system, which continuously monitors the melt pool with the help of sensors [2]. With this real time control of heat input into the clad, the Heat Affected Zone (HAZ) is kept to a minimum and the microstructure is very fine, thus exhibiting properties close to the parent material [3].

Turbine blades also have complicated serpentine cooling channels as shown in Figure 1. The DMD process has been applied for building in the serpentine channel during layer-by-layer fabrication. DMD has also successfully demonstrated deposition resolutions up to 0.26 mm with f/7 optics (see Fig. 2) and even finer resolutions are possible with different optics having shorter f/#'s. Thus, the capability for creating finer features is already demonstrated and has been incorporated in this process to directly

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **FEB 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **Spatial Control of Crystal Texture by Laser DMD Process**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The POM Group, Inc,2350 Pontiac Road,Auburn Hills,MI,48326**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002300. Presented at the Minerals, Metals and Materials Annual Meeting and Exhibition (138th)(TMS 2009) Held in San Francisco, California on February 15-19, 2009. Sponsored in part by the Navy. U.S. Government or Federal Purpose Rights.

14. ABSTRACT
Turbine blades with controlled textures such as directionally solidified and single crystal structures have proven to have much improved ductility and longer thermal and fatigue life. It has been further reported that the benefits of single-crystal over conventionally cast as well as directionally solidified components critically depend on avoiding the introduction of defects, such as stray grains, freckles, or deviations from the required crystal orientation. Laser-based direct metal deposition (DMD) process equipped with proper sensors and NC devices helps in overcoming those hurdles to fabricate the blades with controlled texture. It appears that thermal control to provide uniform heat flow as well as spatial control of crystal texture by process feedback control is essential. The paper discusses about how to establish process conditions and thermal control requirements, development of a laboratory scale DMD process for spatial control of crystal texture, and mechanical properties of texture-controlled Ni-based superalloy turbine blade components.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

fabricate blades from digital data.

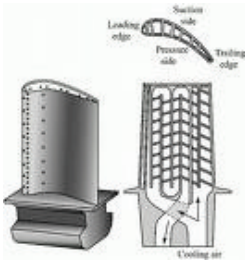


Figure 1. Serpentine cooling channel of blade

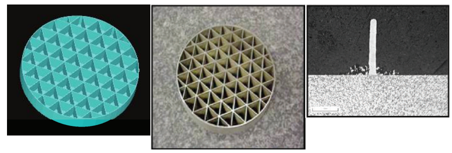


Figure 2. Sample with fine resolution (Wall thickness = 0.26 mm, Material: IN625)

Backgrounds

During solidification of the melt pool obtained by laser/material interaction, the solid acts as a heat sink and solidification is mostly directional, at least locally. The heat flux is opposite to the growth direction and the rate of advance of the isotherms constrains the solid–liquid interface to grow at an imposed velocity. If the feeding material is similar to the substrate, initial solidification shows an epitaxial growth when the substrate is slightly molten. If nucleation and growth of equiaxed grains in the liquid ahead of the columnar front are avoided, an epitaxial, columnar (DS) and SX structure may be achieved throughout the deposit. Therefore, a close control of the columnar to equiaxed transition (CET) is a must condition for successful processing as shown in the case of CMSX-4 Ni-superalloy (Figure 3)[4].

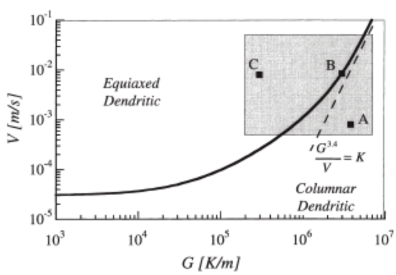


Figure 3. Microstructure selection map for superalloy CMSX-4 under the experimental conditions described in the text, showing the expected solidification morphology as a function of temperature gradient, G, and solidification velocity, V. (Note: The dotted line represents the critical condition for Laser Metal Deposition process, with K = 5 2.73x10^{24} ($K^{3.4}/m^{4.4}$ s). The rectangular insert shows the range of condition, which is typical for the Laser Metal Deposition process. The squares represent average G and V values for laser processing conditions A, B and C. DT_n = 2.5°C, N_0 = 2x10^{15}/m^3, f_c = 0.0066.) [4]

The temperature gradient, G, and the solidification velocity, V, under laser processing conditions are the most important parameters, which govern the solidification structure of a given alloy. For instance, the CET can be characterized by a critical G^n/V ratio. In the practice of laser processing typically, we control the processing parameters, such as laser power P, beam velocity V_b, substrate temperature T_0 or beam diameter D_b, which show complex relationships with the local solidification conditions G and V. G is given by the temperature field generated by the laser source and V is related to beam velocity and the melt pool shape.

Computing the characteristic value of the G^n/V ratio as a function of a set of major processing parameters (T_0, V_b, P, D_b), the complex laser metal deposition process can be simplified. By calculation of the characteristic ratios for several sets of processing parameters as compared with the microstructure criterion, processing–microstructure maps may be obtained. It is only under both simultaneously achieved conditions, i.e. sufficient remelting for epitaxial growth and columnar dendrite growth, that DS as well as SX deposit may be produced.

Some important suggestions about the laser processing conditions for a successful DS and SX deposit has been made as follows:
• The temperature of the substrate should be as low as possible (preheating has to be avoided). – use cold plate (maintaining below 10˚C during the DMD)
• The laser beam power should be reduced as this increases the temperature gradient. (minimum laser power)
• The laser beam diameter should be small in order to ensure sufficient remelting for epitaxial growth. (d = ~1 mm)

Thermal Control of DMD Process

Uniform Thermal Environment and One-dim Heat Flow

It is acknowledged that the melt-pool solidification conditions during laser deposition process generally results in a dendritic microstructure with columnar or equiaxed growth morphologies [4,5]. Since solidification process is strongly influenced by temperature gradient and cooling rate, the crystallographic orientation of the material will be influenced by them during the deposition process. Therefore, they should be managed properly, providing uniform one-dimensional uniform heat flow in the direction of <001>. Especially the competitive growth mechanism among the seeds should be well-controlled, stabilizing epitaxial, columnar dendritic growth and avoiding nucleation and growth of equiaxed grains when a single crystal substrate is used.

Graphic User Interface (GUI) to Control Process Parameters

It is obvious that establishing effective deposition process strategy is very important, securing each layer as a base for the next layer since deposition thickness is mainly determined by the amount of mass flow and specific energy into the melt pool. It is suggested that controlling both laser power and powder mass flow rate is relatively easier than controlling other process parameters such as beam spot diameter or deposition speed with powder mass flow rate, since non-linear factor can be suppressed relatively easily [6]. Commercially available GUI software (e.g. LabView®) is a very effective tool to monitor and control process data, interfacing process devices, performing signal processing, and optimizing process parameters.

Spatial Control of Crystal Texture

Closed-loop Feedback Control of Deposited Material in Space

A technical challenge, in spatial control of the process, is how precisely the dimensions and properties can be maintained and managed. The closer the spatial accuracy, the better is the material performance as designed. Also, substantial cost reduction is possible, if desired properties can be achieved through process control and post-process heat treatment minimized. Through the control of the laser power and powder mass flow the process should be consistent and steady. Implementing a proper solution to control local deposition dimension and material integrity, utilizing optical sensor techniques and a closed feedback control system, will be the key to make it effective and successful. Figure 4 shows a picture of partially finished turbine blade fabricated from scratch by DMD.

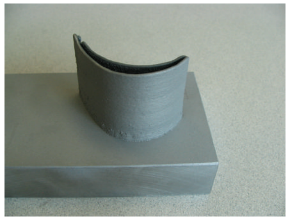
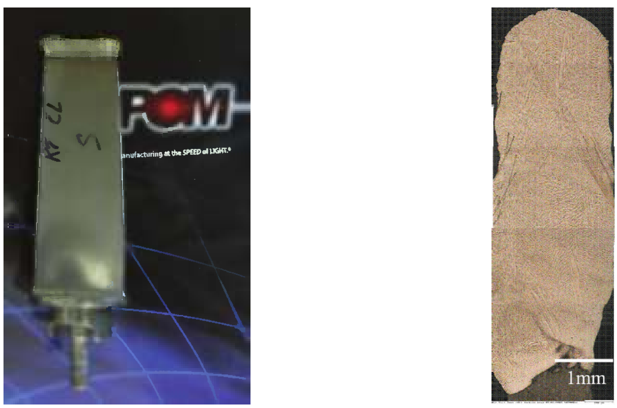


Figure 4. Partially finished turbine blade (Material: IN625)

Figure 5a shows the squealer tip of an airfoil repaired by DMD process. Figure 5b shows cross-section microstructure of the airfoil. Deposited material is IN625 on a stainless steel (A286) base material. Clearly the cross-section depicts epitaxial growth of the Ni-super alloy in the rebuilt region. The growth of <001> texture has been assisted by high temperature gradient that is usually associated with laser metal deposition process. Work is on to develop a repair strategy for these blades utilizing POM's patented close loop technology in order to achieve near net shape in the rebuild part and optimize thermal energy input. This allows minimal post grinding operation and provides the most cost effective solution for turbine blade repair.



(a) (b)

Figure 5. (a) A turbine vane showing the squealer tip repaired by DMD process using IN625, (b) Cross-section microstructure of the same blade showing epitaxial growth of IN625 crystals in the as-deposited material.

DMD of IN718 and IN625

IN718 is a precipitation-hardenable Ni-Cr superalloy containing significant amounts of Fe, Nb, and Mo along with lesser amounts of Al and Ti. It combines corrosion resistance and high strength with outstanding weldability, including resistance to post weld cracking. Meanwhile, IN625 is a Ni-Cr-Mo superalloy with an addition of Nb that acts with the Mo to stiffen the alloy's matrix and thereby provide high strength without a strengthening heat treatment. These Ni-based superalloys were selected and carried out to demonstrate if spatial texture control can be effectively achieved through DMD process. Table I shows the chemical composition of IN718 and IN625, respectively. The size distributions of these powders are shown in Table II and Table III.

Table I. Chemical Composition of IN718 and 625

Element (%)	IN718	IN625

Ni	Bal.	Bal.
Cr	17.90	20.80
Co	0.27	0.02
Mo	2.99	8.69
Al	0.30	0.09
Ti	0.81	<0.01
C	0.03	0.01
B	0.002	0.011
Zr	-	-
Ta	-	0.01
W	-	-
S	0.001	<0.010
Si	0.05	0.09
Mn	0.12	<0.01
Cb(+Ta)	5.02	3.29
Cu	0.22	-
Fe	18.04	0.40
P	<0.010	<0.015

Table II. Size Distribution of IN 718

US Mesh +100	US Mesh -120+325	US Mesh -325
0.42 %	97.72 %	1.86 %

Table III. Size Distribution of IN 625

US Mesh +120	US Mesh -120+325	US Mesh -325
0.0 %	94.0 %	6.0 %

After process parameters have been optimized, generic airfoils (Note: design provided by GE Transportation) were built up from substrate material (Cold Roll Steel). In order to enhance metallurgical bonding between substrate and DMD material, a couple of intermittent layer of IN625 were deposited on the substrate and then DMD material (IN718 or IN625) were deposited.

Texture Control by DMD

Figure 6 shows generic turbine blade sample made of IN718. The surface shows DS textures interrupted, which were caused due to the grinding at specific layered surfaces indicated in the Figure 6. The DMD build-up of IN718 has been a bit more difficult than that of IN625, since IN718 has both lower thermal conductivity and thermal diffusivity at elevate temperature. It occasionally resulted in sagging phenomena at the front and tail location, where process velocity was decelerated, although POM's DMD closed feedback control unit was activated, controlling for necessary laser energy input. Nonetheless, aggressive control of laser input energy intermittently affected thinning (or wavy) wall thickness of airfoil, which is not desirable. In order to improve both the flatness and unswerving width of deposit surface, as a remedy, laser beam size, i.e. melt pool size, should be maintained consistently by monitoring surface temperature at the melt pool.

Figure 7 shows turbine blade sample made of IN625. After polishing the surface of airfoil, DS texture was, in most samples, observed. Aforementioned sagging phenomenon was drastically reduced, and in most DMD cases, the layered deposition was smooth and solid. As noticed in the Figure 7, the direction of texture was not exactly perpendicular to the building direction, but it was measured about 60 degree or higher from the substrate. It is believed that the texture angle is influenced by both the process traverse speed and cooling rate (or solidification rate).

Figure 6. (a) Front view of generic airfoil (IN718) showing interrupted DS texture due to grinding of the layered surface, (b) Top view of the airfoil

Figure 7. (a) Front view of generic airfoil (IN625) showing interrupted DS texture due to grinding of the layered surface, (b) Top view of the airfoil

In order to study the direction of texture after DMD, the surface of airfoil was sectioned and SEM analysis was carried out to examine texture pattern (Figure 8(a)). It appeared that the directionality of texture in each section keeps usually consistent. Dendritic (or grain) growth is following the direction of solidification, as layers are built up on the top of previous layer. As shown in Figure 8(b), interestingly two different direction of grain growth have been merged and grown in one direction. The angle between two competing grain growths was measured as less than 15 degrees for almost all of those grains (or dendrites), which can be called as “DS structure”.

Figure 9 shows the induction coil system assembled with DMD machine for texture control during DMD process. The induction coil system, rented from Induction Atmospheres System (Rochester, NY) and controlled by a heat station with 12kW power supply (Fives Celes) was employed. The induction coil geometry was fabricated, based on generic blade profile in order to maintain uniform temperature around the airfoil perimeter. To make a hybrid process of DMD and induction heating synchronized and working effectively, two-color type thermometer sensor (pyrometer) was utilized. Nevertheless, it turned out that maintaining uniform temperature around the perimeter of airfoil with the pyrometer was not that effective, since the two-color pyrometer equipped with the induction coil system was not dynamic enough to control and keep the temperature uniform and consistent, as the laser melt pool travels around the airfoil profile. As the melt pool approaches to the location illuminated and spotted by the pyrometer sensor, the sensor starts to control the power supply of the induction coil system down as the temperature gets increased. As it passes away the location aimed by the pyrometer, thereby the temperature gets decreased, the power supply turns up and the induction coil gets hot. The control is good only at the spot of the aimed pyrometer since it looks at one location, not all the profile of the airfoil, therefore, control effectiveness of the induction coil via. power supply was almost not fully-implemented. As a remedy,

temperature sensors, which can keep steady and uniform, should be implemented, monitoring and controlling the temperature on the deposited surface.

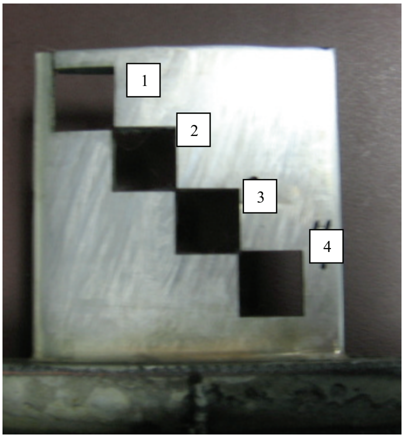
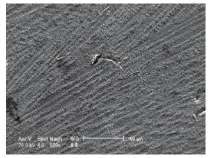
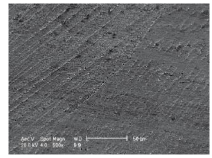


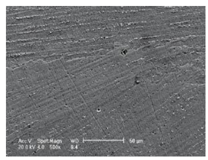
Figure 8. Surface texture of generic airfoil (material: IN625, ~2” wide, ~2” high)



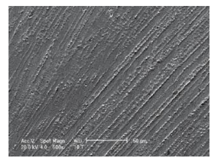
(a) SEM taken from area 1



(b) SEM taken from area 2



(c) SEM taken from area 3



(d) SEM taken from area 4

Figure 10 shows the surface texture after the induction coil system (at 2200 deg-F). The area affected by the induction system shows random poly-crystalline/equiaxed grain development. From this experiment it was found that the uniform temperature control of induction coil system is an essential to control texture pattern during this hybrid process of DMD and induction coil heating. Provided with better temperature controlled induction coil system, the hybrid process (DMD and induction coil melting) may be performed more effectively to control spatial texture growing during DMD/induction process.

Mechanical properties of DMD fabricated materials are as good as present materials in the poly-crystalline form. Table IV provides sample data and DMD demonstrates that conventional defects such as porosity or micro-cracks are totally absent. In addition, controlling the cooling rate via process parameters can modify material properties. As spatial texture control using DMD is fully put into operation, high quality can be expected.

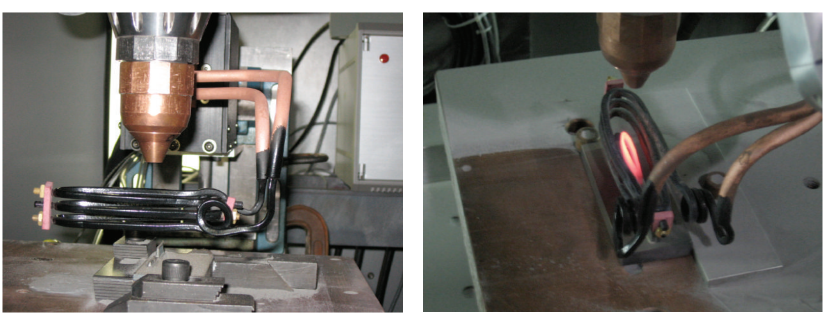


Figure 9. Induction system assembled with DMD process

Figure 10. Generic blade made of IN718 after induction heating at 2200 deg-F

Table IV. Comparison of mechanical property data between DMD fabricated and Commercial materials

Material	Data source	Material	Specimen axis	Tensile strength (Mpa)	Yield strength (Mpa)	Elongation (%)	Elastic Modulus (Gpa)	Charpy Impact Energy (J)	Hardness (HRC)
In 625	POM	In 625 DMD	Transverse to crystal growth	795	598	14	187	101.6	13
	Matweb	In 625, 927C annealed & aged	Parallel to rolling direction	897	483	40			15.7
	Matweb	In625, filler material		687	414	30			
IN 718	POM	In 718 DMD	Transverse to crystal growth	928	630	19.3	207	61	40.5
	Matweb	In718 annealed & aged	Parallel to rolling direction	1120	827	31	205		24
	Matweb	In718 filler material		1140	414				

Summary

Spatial control of crystal texture by DMD has been attempted and DS microstructure of IN718 and IN625 was implemented. There is still a room to refine the texture control more effectively by adding induction coil system with multiple temperature sensors. During the deposition of multi-layer deposits, especially in the case of thin wall-shaped deposits, the temperature gradients in the melt pool decrease as the number of layers increases, due to the change of the thermal conduction conditions in the deposit. To minimize the change of the condition and maintain one-dim heat flow, the temperature at the substrate should be kept constant putting on cold plate. In addition, laser power should be adjusted accordingly to keep the G^n/V ratio above the critical value for maintaining the columnar dendritic growth as the number of layers increases by closed-loop feedback control capability of DMD.

Acknowledgement

Authors gratefully acknowledge financial support from DARPA SBIR Phase I grant (W31P4Q-08-C-0209). Dr. William Coblenz is the program monitor.

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